REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
01-MAY-2002	Conference Proceedings, (not refereed)	01-MAY-2001 02-APR-2002

4. TITLE AND SUBTITLE

Observations of Velocities and Orientations of Cylindrical Bodies at Terminal Condition in Water

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

PHILIP J VALENT   K TODD HOLLAND   Albert W. Green   STEPHEN THEOPHANIS
LCDR C. KING   MICHAEL D RICHARDSON   GRANT BOWER   Peter Congedo   Bill Lewis

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Marine Geoscience Division
Stennis Space Center, MS 39529-5004

8. REPORTING ORGANIZATION REPORT NUMBER

NRL/PP/7400--02-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

NRL
STENNIS SPACE CENTER, MS 39525

10. SPONSOR/MONITOR'S ACRONYM(S)

NRL

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release,distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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15. SUBJECT TERMS

CYLINDRICAL BOTTOM MINE MODELS

20021025 332

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE
unclassified	unclassified	unclassified

17. LIMITATION OF ABSTRACT

UNLIMITED

18. NUMBER OF PAGES

-9-

19a NAME OF RESPONSIBLE PERSON

PHILIP J. VALENT

19b. TELEPHONE NUMBER (Include area code)

228-688-4650

Standard Form 298 (Rev. 8/98)

Observations of Velocities and Orientations of Cylindrical Bodies at Terminal Condition in Water

P.J. Valent[1], K.T. Holland[1], A.W. Green[2], S. Theophanis[1], C. King[1], M.D. Richardson[1],
G.R. Bower[1], P. Congedo[3] and W. Lewis[3]

Abstract: Trajectories of 1/3rd-scale and full-scale cylindrical bottom mine models falling in the water column are found to be much more complex than predicted by a present impact burial prediction model. For cylinders released in air, air bubbles trapped when the cylinder enters the water appear to dampen turbulent boundary effects resulting in stable trajectories while the bubbles remain attached. With loss of trapped air bubbles during descent through the water, turbulent wake and boundary layer effects generate a wide range of motion and lateral excursion. This paper offers some preliminary projections for the extent of cylinder excursion and for orientations and velocities to be expected at the bottom.

I. INTRODUCTION

Objective: This paper summarizes the behavior of mine-like, cylindrical shapes during water entry and fall through the water column observed in 203 releases of 1/3rd-scale models in a 8 m deep test pond and 11 releases of a full size model in a 15 m deep littoral environment.

Motivation: During deployment, anti-ship bottom mines can penetrate into soft cohesive sediments with the orientation and depth of penetration depending on cylinder size, length-to-diameter ratio, mass, and shape of ends (influencing cylinder velocity and orientation at the mudline) and sediment shear strength and density. Detection of fully buried mines is a very difficult, time consuming and uncertain task. Reliable prediction of the probability of encountering buried anti-ship mines is critical to planning mine clearance operations (or area avoidance). The goal of the Office of Naval Research (ONR)/Naval Research Laboratory (NRL) Mine Burial Program is to improve the Navy's capability to predict extent of mine impact burial for expected mine types at any location.

Prior Work: A framework for a mine impact burial prediction model was first published [1] and then improved by [2]-[4]. Lab testing of uninstrumented mines [5] and field testing of an instrumented, cylindrical, full-size shape [6] showed that model predicted orientations and penetrations differ significantly from measured orientations and penetrations. Further, analysis of data from 16 test drops showed that the hydrodynamic section of the impact burial model was contributing significantly to the orientation/penetration errors observed.

Work Reported Here: Preliminary results of two test series are reported. Test drops of 1/3rd-scale models were conducted 10-14 September 2001 in the Explosion Test Pond at Naval Surface Warfare Center Carderock Division (NSWCCD). The scaling factor of 1/3rd was selected to hopefully make the models sufficiently large so as to hydrodynamically behave similarly to prototype cylindrical mines while keeping the models light enough so as to not damage the bottom of any test tank to be used. Using six models sized to represent the range of cylindrical bottom mine types, 75 releases from 1-to-2 m above the water surface and 128 releases from 0.15 m below the water surface were carried out. The 1/3rd-scale models carried no sensors. The orientation and trajectory data were obtained by high speed analog and digital video cameras mounted above and below the water surface. This series of 1/3rd-scale model tests have provided critical data for improvement of the water column portion of the impact burial prediction model.

To obtain data for improvement and validation of the sediment penetration portion of the burial model, a generic bottom mine was designed, fabricated, assembled and tested representing the mean size, length-to-diameter ratio, mass, and center of mass (CM) versus center of volume (CV) offset. Those environments offering soft cohesive (mud-like) sediment seafloor reachable by divers (needed to make measurements of cylinder embedment and to connect recovery line) are turbid enough to prevent optical measurements, especially near the seafloor, requiring that the cylinder have an internal sensor and data recording system to obtain cylinder orientation, trajectory, and velocity during free-fall and seafloor penetration. The full-size 1017 kg (2,242 lb) cylinder with internal fiber optic gyro (FOG) and 2-, 4- and 10-g accelerometers was tested successfully in 11 drops in 15 m water depth off Cocodrie, LA, 8-9 January 2002.

1. Naval Research Laboratory, Stennis Space Center, MS 39529
2. Omni Technologies, Inc., New Orleans, LA
3. Naval Surface Warfare Center Carderock Division, West Bethesda, MD

II. ONE-THIRD SCALE MODEL TESTS

Description of Models and Experiment Set-up: Six 1/3rd-scale cylinders were fabricated from standard aluminum pipe sections 0.168 m diameter with plate ends (see Figure 1 for design dimensions and masses of models). Weighting in the form of aluminum and steel discs with water filling the remaining void space was added to the inside of the cylinders to adjust the overall bulk density of the cylinders to 1.60 or 2.10 Mg/m³. The urethane noses of the cylinders were fastened to the cylinder end on 3/4-in. (19 mm) threaded studs enabling interchange of hemispherical and blunt noses. The internal weighing plates were mounted on 3/8 in. (9.5 mm) steel threaded rods with plate locations adjusted and fixed to maintain desired CM location. Table 1 summarizes as-built characteristics of the six models shown in Figure 2.

Operators of a number of water-filled research tanks were approached in search of a suitable, clear water test facility with most declining when the discussions reached the issue of impacting 46 kg cylinders at 4 m/sec on the tank floor. Operators of the Explosion Test Pond at NSWCCD were the only folks agreeable to applying that forcing to the floor of their facility. The Explosion Test Pond (see Figure 3) proved to be ideally suited for the hydrodynamic experiments.

For the tests, the cylinders were suspended from a line from a crane boom, maintained at the same position for all tests. Four high speed digital and five analog video cameras were arranged in one quadrant of the pond to view the water entry and fall through the upper 6 m of the water column. Usually all six cylinders were dropped sequentially as a group and, after the group drop, divers attached a line from the crane for speedy recovery. The cylinders were released from a Pelican hook with electric powered solenoid release. The circuit powering the Pelican hook also triggered the video recordings.
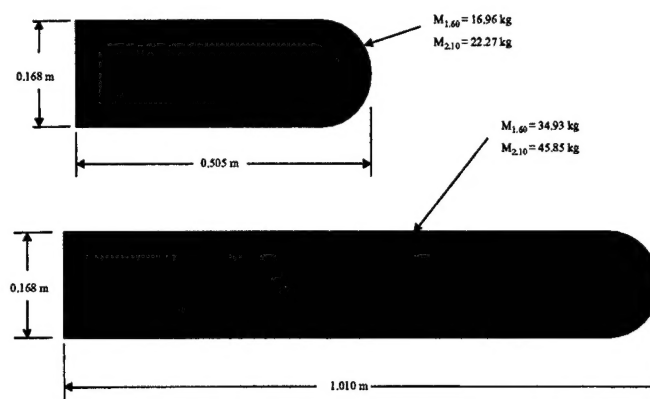

Figure 1. Sketches of 1/3rd-scale models, as planned for use in NSWCCD Test Pond. Models shown with hemispherical noses.

Model number	1	2	3	4	5	6
Diameter, m (in.)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)
Length, hemi, m (in.)	0.505 (19.88)	0.505 (19.88)	1.010 (39.75)	1.010 (39.75)	1.010 (39.75)	1.010 (39.75)
L/D for hemi nose	3	3	6	6	6	6
Length, blunt, m (in.)	0.477 (18.78)	0.477 (18.78)	0.982 (38.65)	0.982 (38.65)	0.982 (38.65)	0.982 (38.65)
L/D for blunt nose	2.8	2.8	5.8	5.8	5.8	5.8
Volume, cu m (cu ft)	0.0106 (0.374)	0.0106 (0.374)	0.0218 (0.771)	0.0218 (0.771)	0.0218 (0.771)	0.0218 (0.771)
Weight (lbs)	38	49	76	102	100	98.5
Mass, kg	17.2	22.2	34.5	46.3	45.4	44.7
Bulk density, pcf (Mg/cu m)	101.6 (1.63)	131.0 (2.10)	98.6 (1.58)	132.3 (2.12)	129.7 (2.08)	127.8 (2.05)
Ctr Volume from tail for hemi, m (in.)	0.239 (9.39)	0.239 (9.39)	0.486 (19.15)	0.486 (19.15)	0.486 (19.15)	0.486 (19.15)
Ctr Mass from tail for hemi, m (in.)	0.238 (9.38)	0.236 (9.31)	0.484 (19.06)	0.478 (18.81)	0.533 (21.00)	0.565 (22.25)
(CM - CV) / (mine length)	-0.0005	-0.004	-0.002	-0.009	0.046	0.078
Moment of Inertia about CM						
I_{xx}^1, kg–m² (lb–in²)	0.0647 (221)	0.0806 (275)	0.1362 (465)	0.1696 (579)	0.1693 (578)	0.1692 (578)
I_{yy}^2, kg–m² (lb–in²)	0.356 (1216)	0.477 (1627)	2.90 (9910)	3.82 (13,050)	3.94 (13,440)	4.57 (15,600)
I_{zz}^3, kg–m² (lb–in²)	0.356 (1214)	0.476 (1625)	2.90 (9910)	3.82 (13,050)	3.94 (13,430)	4.57 (15,600)
Note:						
1. I_{xx}, about long axis (Roll)						
2. I_{yy}, about transverse vertical axis (Yaw)						
3. I_{zz}, about transverse horizontal axis (Pitch)						

Table 1. Physical characteristics of cylindrical models used in 1/3rd scale tests, NSWCCD Explosion Test Pond, West Bethesda, MD, 10-14 Sep 2001.
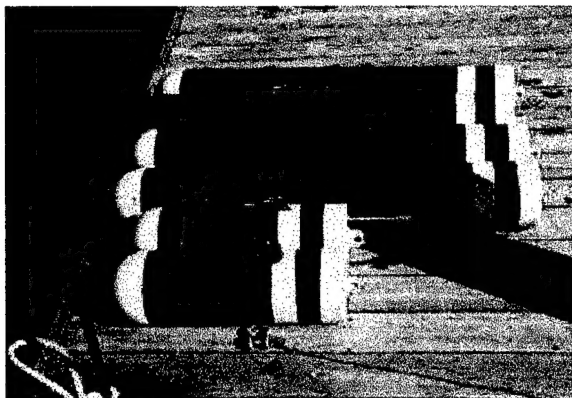
Fig. 2. Six 1/3rd-scale models shown with hemispherical noses. Model numbers are 1 through 6 in order from bottom (short brown cylinder) to top (long black cylinder). Note white and yellow bands and ends used as reference point.

Figure 3. Explosion Test Pond facility, Naval Surface Warfare Center Carderock Division, West Bethesda, MD, location of 1/3rd-scale model experiment.

The models were released from orientations of long axis horizontal and inclined nominally 45° and vertical nose down. For those releases with the models submerged, the nose down angle ranged from 35 to 50° because of the buoying force of the water and our inability to relocate positions of lifting lugs after discovering the problem during the testing. The models were released from altitudes of 0.5, 1.0, 1.5, and 2.0 m over the water surface and 0.15 m below the water surface.

Results and Observations: A four-camera analyzer sampled high-resolution, color recordings at speeds of 250 full frames per second (fps) for the in-air portion of the mine fall and 125 fps for the underwater portion. The digital images from the four high-speed imagers were transmitted via Ethernet cable to an image-processing computer for near real-time analysis. The image-processing computer was equipped with advanced motion analysis software to track the 3-D (x, y, z) location of various points on the mine over time. (The white and yellow paint banding on the models, shown in Figure 2, served as reference points at tail and nose of each model for tracking by the analysis system.) Of the 203 cylinder drops conducted, 170 were adequately tracked/processed by the automatic tracking system. For those models released in air, the bubble cloud formed during water entry often obscured the model; consequently, video tracking was difficult, or impossible in those cases. NRL processed the x, y, z, t data to calculate instantaneous and average vertical speeds and velocities, and instantaneous pitch and azimuth for each data set (see Figure 4). Average vertical speed data were also generated from manual processing of the analog video data.

Data from the 1/3rd-scale model tests have been distributed to hydrodynamics modelers in the ONR Mine Burial Program [Professors Dick Yue, Massachusetts Institute of Technology (MIT) and Peter Chu, Naval Postgraduate School (NPS)] for use in hydrodynamic model development for the water column portion of the impact burial model. We believe the 1/3rd-scale model data set to be very valuable and anticipate that this data set may be useful to others. This data set will be made available by ONR beyond the ONR project team for further exploitation after March 2003.

Preliminary observations from this 1/3rd-scale model test series are:

- Typical fall speeds of $^1/_3$ - scale models ranged from 1 to 4 m/s although speeds of up to 6 m/s were observed.
- Typical lateral excursion ranged from 0.5 to 1.5 m in 4 m fall.
- When the CM is located near the CV [(CM-CV)/(Cylinder Length) < 0.05], there

is strong tendency for cylinders in free-fall to orient with maximum area presented to direction of travel. (Note: This is not an original observation by the authors, but is proposed to be the case in analytical work [5] and [7]).

- When cylinders enter the water, trapped air bubbles dampen turbulent boundary layer effects.

- With loss of trapped air bubbles, turbulent wake and boundary layer effects generate wide range of motion and lateral excursion.

III. FULL-SIZE MODEL TESTS

Description of Cylinder, Instrumentation, and Experiment Set-up: The full-size instrumented model is fabricated from a cast bronze cylinder 0.533 m diameter and 25 mm wall thickness with 25 mm thick bronze end caps (see Figure 5). The bronze end caps are fitted with circumferential and face O-ring seals protecting two battery packs containing 144 D-cells mounted near the tail of the cylinder. The fiber optic gyro (FOG), accelerometers and PC controller and data storage are all housed in a second pressure housing mounted within the outer bronze shell with the center of the FOG positioned at the CM of the model. Aluminum plates with lead bricks attached were added within the bronze shell to bring the total mass up to 1,017 kg and positioned so as to locate the CM 0.104 m forward of the CV. The hemispherical nose slides and is locked into a collar attached to the front of the bronze cylinder.
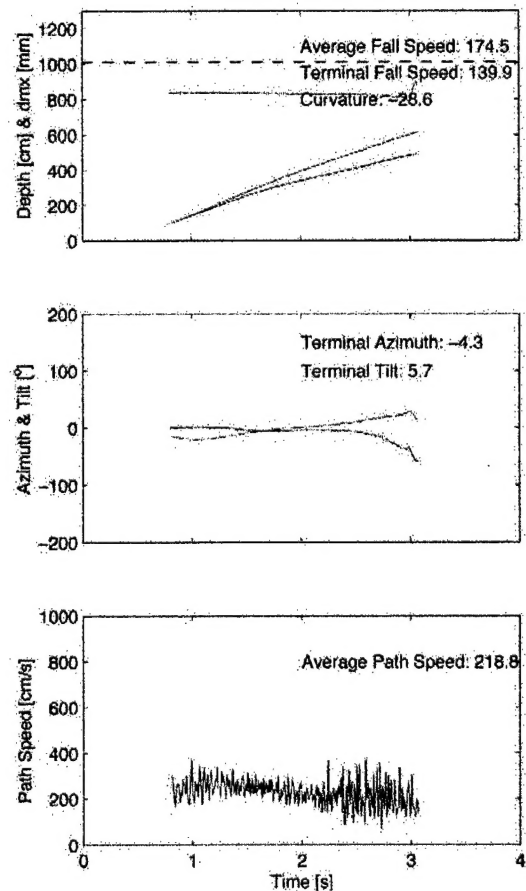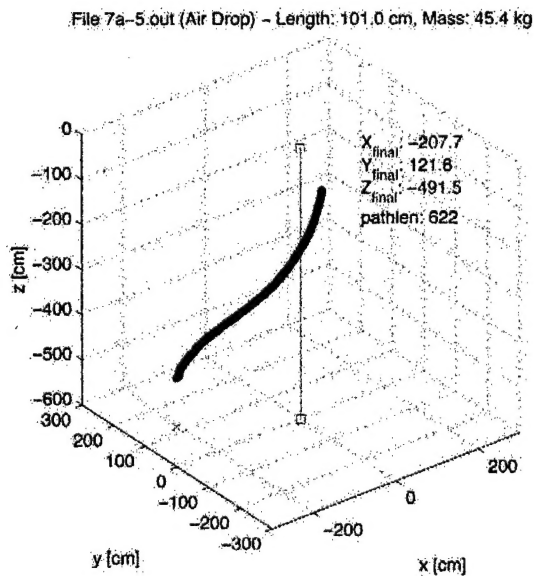

Figure 4. Typical product from one 1/3rd-scale model test, one of 170 successfully processed by the digital camera system out of 203 drops. Left side panel shows fall trajectory. Right side of figure shows azimuth, tilt, path speed, and fall speed characteristics.

Mass = 1,017 kg
Bulk density = 1.92 Mg/m^3
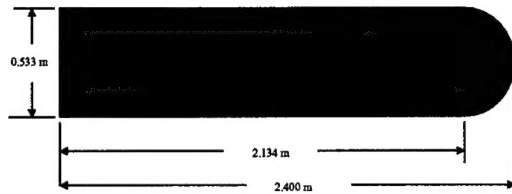

0.533 m

2.134 m

2.400 m

Figure 5. Sketch of exterior of full-size, instrumented cylinder used at Cocodrie, LA, shown with hemispherical nose.

This mounting system allows the hemispherical nose to be interchanged with blunt and chamfered noses to be used in future experiments. The noses are fabricated on aluminum plates with aluminum and steel plates added to bring the bulk density of the complete nose up to 2.1 Mg/m^3. Urethane is then cast over the metal plates to provide the external shape (see Figure 6).

The purpose of the 8-9 January tests from the R/V PELICAN was to field test the sensors, PC controller and data acquisition system, and project-specific, in-house software and technique for extracting cylinder trajectory, orientation and velocity from the FOG and accelerometer data. For this purpose we first picked a platform capable of handling the cylinder and operating near NRL Stennis Space Center, the R/V PELICAN, and then asked the PELICAN's captain to take us out to 15 m water depth over a soft mud seafloor. Six drops and recoveries were carried out the first day and five the second – by the second day, the time required for completing one cylinder drop-and-recovery evolution had been reduced to 60 minutes.

The cylinder was released in air five times from distances over the water from 0.2 to 1.0 m, and in water six times from 0.5 m below the surface. The orientations used were long axis horizontal and 45° nose down. In all cases, the cylinder carried with it two-inch wide nylon straps varying in length from 1-to-2 m used in rigging for single point release and to reduce diver time required to connect a recovery line (Figure 7). The cylinder was released with a 6 mm nylon tag line attached to the tail for the divers to

follow in descending to the cylinder on the seafloor (Figure 8).

Lateral excursion and direction of travel, and cylinder heading, depth of embedment, and pitch of the cylinder were all measured. A few seconds before release of the cylinder, a 7 kg lawn-dart like stake, with 19 mm diameter by 0.6 m long solid steel shaft, was dropped from near the cylinder trailing a 6 mm nylon line, to mark the location on the seafloor directly below the point of release (save for offset by currents during fall to the seafloor). Compass heading from dart to cylinder and heading of the cylinder nose were taken immediately prior to release. After the cylinder had reached the seafloor, two divers entered the water, one to follow each 6 mm nylon line to the seafloor (one to the cylinder and one to the stake). The divers carried another line between them as a signal line and to measure the lateral excursion of the cylinder. The diver going to the cylinder carried the bitter end of the line. The diver going down to the stake pulled the inter-diver line taut and tied a knot in that line to mark the distance from stake to cylinder on the seafloor, and then aligned a recording compass with the taut line to record the bearing from stake to cylinder. Bear in mind, the divers are working in near zero visibility because of the extreme turbidity near the mud seafloor. Upon completing the knot tying and recording heading to the cylinder, the diver at the stake would pull himself along the line to the cylinder. At the cylinder the divers would record the heading of the cylinder on the seafloor and the position of the mudline on the cylinder at tail and nose and would estimate the pitch nose down of the cylinder. Other relevant observations such as sediment mounding at the nose, gaps between cylinder side and the sediments, etc., were noted. At this Cocodrie, LA site, the cylinder embedded in the sediments about one-half way with the nose pitched down 1-to-35°. The last step for the divers on the seafloor was to attach a lift line from the ship's trawl winch for cylinder recovery. When the cylinder was safely on deck, the data umbilical was connected to the data port at the tail of the model, the data siphoned off, and the PC controller programmed for the next drop.

Figure 6. View of nose end of instrumented cylinder. Black material is urethane cast on aluminum plates comprising the detachable nose section.

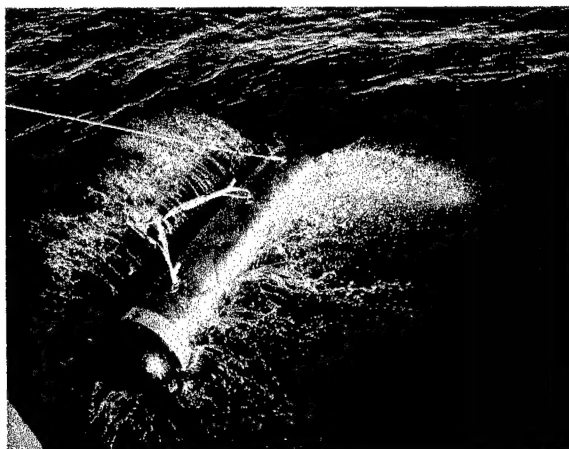Figure 7. View of tail end of instrumented cylinder.

Figure 8. View of instrumented cylinder entering water after in-air release from horizontal orientation. White line to tail is 6 mm diameter nylon tag line used by divers to locate the cylinder on the seafloor in the near-zero visibility of the near bottom water column.

Results and Observations: Data downloaded from each drop were processed immediately to yield orientation and accelerations vs. time and stored on CD's. These processed FOG and accelerometer data were then further processed using in-house software producing cylinder orientation and trajectory plots similar to those of Figure 9.

The first generation of trajectory plots is initialized assuming that the cylinder is at rest at time of release when if fact the cylinder is swinging to and fro with roll, pitch and heave of the ship. This first generation processing concludes indicating that the cylinder still has some velocity when we know it has stopped moving in the mud. This residual velocity is assumed to represent the initial velocity of the cylinder, carried through the data processing. This velocity was applied as an initial velocity to the cylinder in initializing a second generation of trajectory plots, producing cylinder trajectories that look reasonable and lateral excursions and pitch nose down in the sediment that agree with diver observations in most cases. The exceptions are those cases where the cylinder was released in air with nose down 45°. For those cases (Drops #4, #5 and #9, Figure 9), after application of our velocity correction, the water depths calculated still do not agree with the ships depth sounder and/or the lateral excursion and direction of excursion still do not agree with the diver observations. The authors surmise that the FOG system response rate is not sufficient to resolve the rapid rotation of the model as it enters the water.

Data from these full-scale model tests have been distributed to the hydrodynamic modelers and to sediment penetration modelers in the ONR program [Professors Wayne Dunlap and Charles Aubeny, Texas A&M University (TAMU)]. As with the 1/3rd-scale model data set obtained at Carderock, the authors expect that this full-size model data set may have application beyond the ONR/NRL impact burial project, and this data set may be made available by ONR beyond the ONR project team for further exploitation after March 2003.

Preliminary observations from this first test of the 2nd-generation instrumented impact burial mine-shape are:

- The FOG - accelerometer sensor system accurately depicts cylinder dynamics during release, fall and impact burial in muds, with exception of 45° nose-down in-air releases.

- Dynamics of the full-size model during fall are similar to the 1/3rd-scale model (#5).
- Vertical speed at mudline averaged 4.4 m/s with range of 3.7 to 5.1 m/s.

has excluded data from releases from vertical nose down orientation because no such releases were carried out with the full size model at Cocodrie, LA (Vertical nose down releases were excluded from the Cocodrie, LA test because we learned in the 1/3rd-scale model tests that perfectly vertical releases
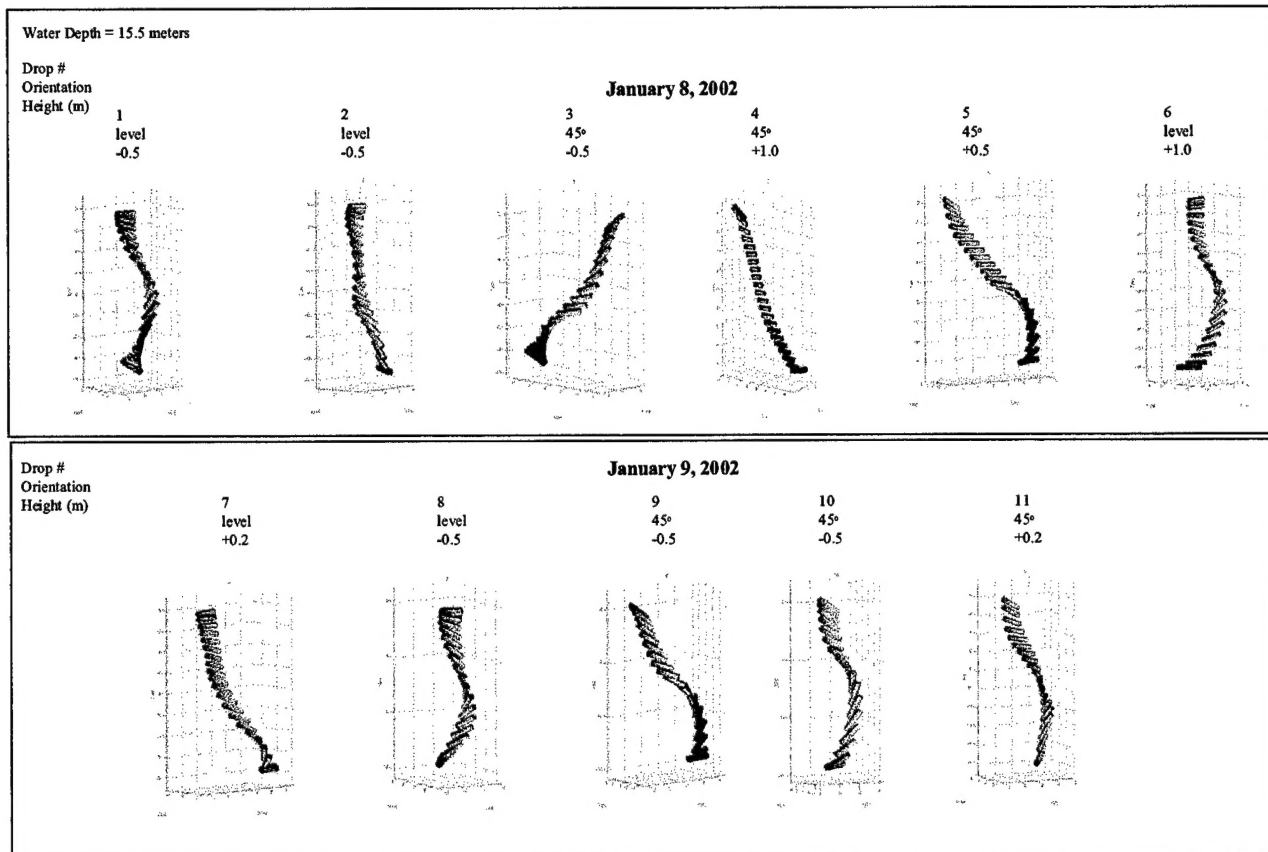

Water Depth = 15.5 meters

Drop #
Orientation
Height (m)

January 8, 2002

1	2	3	4	5	6
level	level	45°	45°	45°	level
-0.5	-0.5	-0.5	+1.0	+0.5	+1.0

Drop #
Orientation
Height (m)

January 9, 2002

7	8	9	10	11
level	level	45°	45°	45°
+0.2	-0.5	-0.5	-0.5	+0.2

Figure 9. Trajectories or instrumented cylinder over 1.5 m water depth recorded in eleven releases from assorted initial conditions. Nose of cylinder in red, and tail in pink.

- Lateral excursions during fall were up to one-half water depth, consistent with observations during the 1/3rd-scale model tests.

IV. PRELIMINARY COMPARISONS OF MEASURED AND PREDICTED VERTICAL SPEED AT MUDLINE

Figure 10 presents a comparison of a group of measured vertical speeds at "mudline" from the tests reported above with predicted vertical speeds from the impact burial prediction model. The comparison

demonstrated a unique behavior. Under certain circumstances they did not begin to rotate to non-vertical before having fallen straight to the pond floor. Because vertical releases exhibit this unique behavior, and because a perfectly vertical release in a real mine laying operation is highly unlikely, we have excluded the vertical nose down orientation from the full-size experiment program.) The Figure 10 comparison also excludes data from the in-air releases because the speeds of some data sets indicated the model was still accelerating from its water entry speed. Thus, the measured data shown in Figure 10 are limited to results of in water release from long axis horizontal and inclined nose down.

The buoyancy parameter used in Figure 10 is $(\rho_{cyl} - \rho_w) / \rho_w$ where ρ_{cyl} is the bulk density of the cylinder and ρ_w is the density of water at the test location. The error bars on data points indicate one standard deviation for the mean value.

Model 5, that most closely representing the CM offset of mines of interest, exhibits a mean speed very close to two other "heavy" models, Models #2 and #4, but with at much greater standard deviation, reflecting a more chaotic behavior. Model #6, with CM located furthest forward, exhibits greater than 1 m/s vertical speed increase over the other five models because Model #6 is maintained at a steep nose down orientation by the CM offset from the CV. Very preliminary comparison of the 1/3-scale model speeds with those of the full-size model suggests that the drag coefficient is different for the two body

speeds. The impact burial model is seen to do a poor job of predicting vertical speeds for Models #4 and #6, both long, heavy models. Further, the impact model does a very poor job of predicting speed for Model #5 and the full-size cylinder, those models most closely representative of mines of interest.

V. SUMMARY

The 203 1/3-scale model tests carried out at NSWCCD served well to highlight the chaotic nature of the cylinder fall through the water column. In the absence of air bubbles accompanying water entry, the cylinders were seen to translate laterally, rotate about a vertical axis through the cylinder, rotate from near horizontal to near vertical, and combinations of the above during free-fall to the pond floor. These
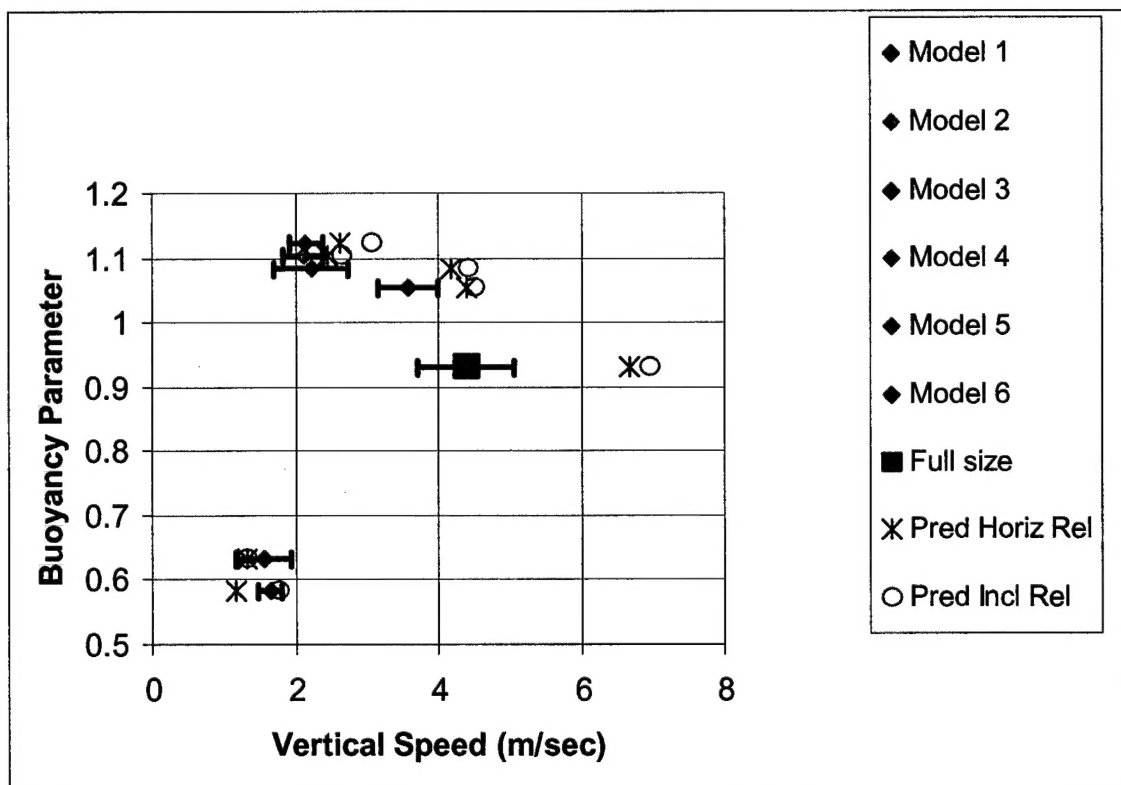

Figure 10. Measured versus impact model predicted vertical speeds: (a) for 1/3rd-scale tests in Test Pond, at end of video viewing area, about 6 m water depth, and (2) for full-size tests off Cocodrie, LA, at first contact with seafloor. Only results of releases from in-water, long-axis horizontal and inclined nose down presented here. Buoyancy parameter is: (density cylinder minus density water) / (density water).

sizes, and this result suggests the two body sizes are described by different Reynolds Numbers; i.e., direct scaling of performance from 1/3rd-scale models up to the full size in not appropriate.

The more interesting comparison of Figure 10 is that between measured and impact model predicted

boundary layer-induced dynamics are somewhat more complex than the behavior predicted by the deterministic model in the impact burial prediction model.

The eleven full-scale model tests conducted from the R/V PELICAN in 15 m water depth near Cocodrie,

LA, demonstrated the robustness of the internal sensing and data acquisition system, and provided a learning experience in how the data obtained could be processed to yield trajectory, orientation and velocity of the falling mine in the water column and sediments. The full scale at-sea tests also demonstrated chaotic behavior during fall in the water column as seen in the $1/3^{rd}$-scale model tests.

Comparison of experimental results with predictions of the impact burial prediction model indicate that the model predicts vertical speeds that are 150% greater than speeds found in our work for expected cylindrical bottom mine types. Improvements to the hydrodynamic portion of the impact burial model must bring these erroneous predictions into line with measured data in order to generate realistic cylinder kinetic energy predictions for the sediment penetration portion of the model.

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